Physics Considerations in the Design of NCSX

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Australia, Austria, Germany, Japan , Russia, Spain, Switzerland, Ukraine

National Compact Stellarator Experiment (NCSX)

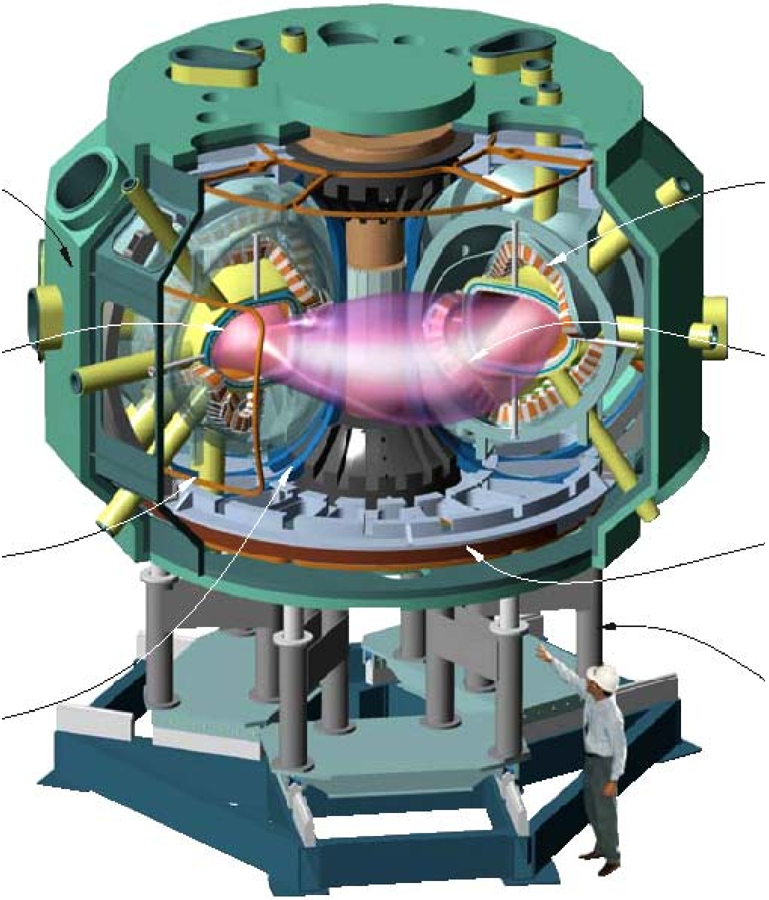
Motivation and Goals

Stellarators have advantages for MFE:

- Steady-state operation w/out current drive.
- Avoid disruptions w/out active feedback.
- 3D shaping: Ample design freedom to optimize properties.

NCSX: test physics concept using tokamak-stellarator synergies:

- **Quasi-axisymmetric (QA)** B–field with low ripple to reduce orbit widths, ripple transport, flow damping.
    - Tokamak-like transport properties?
- High-beta at reduced aspect ratio (≤ 4.4)
- Bootstrap current to generate some (~25%) of the rotational transform ("iota").



NCSX

Coil and VV prototypes in 2003

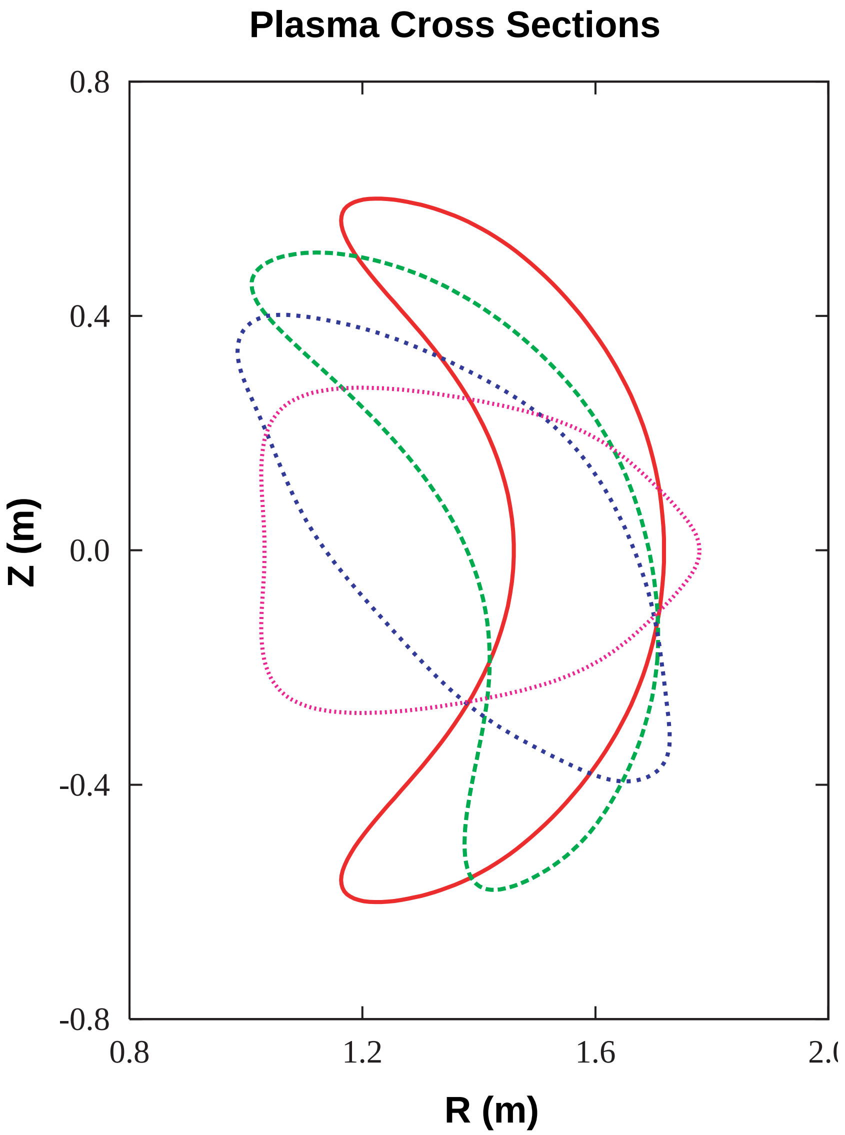
First Plasma in 2007

Key Physics Considerations in the NCSX Design

- Optimize for a β=4% QA stellarator target equilibrium.
  - Test of quasi-symmetry in HSX: J. N. Talmadge, et al., EX/P3-22.
- Ability to access target state starting from vacuum.
- Flexibility to test physics, accommodate profile variations.
- Space for divertors.

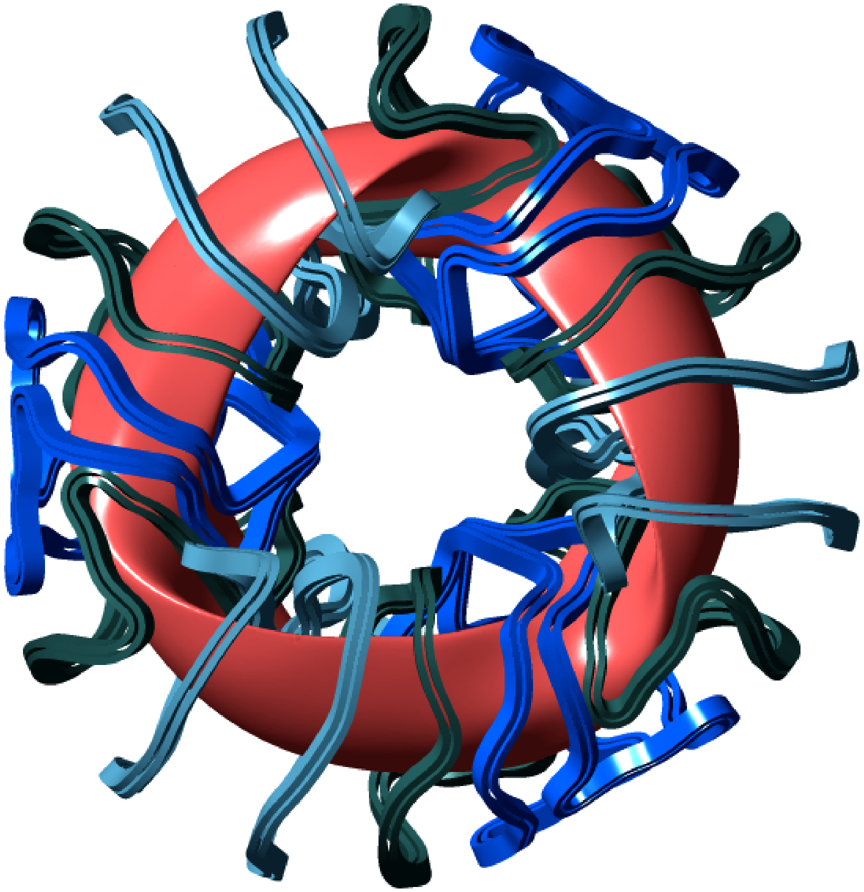
NCSX Target Equilibrium Has Attractive Properties

- 3 periods, low R/⟨a⟩ (4.4).
- Quasi-axisymmetric w/ low ripple.
  - $\varepsilon_{h,eff}$ = 0.1% in core, 2% at edge.
- Stable at β=4.1% to ballooning, kink, vertical, Mercier modes, w/out conducting walls or feedback.
- “Reversed shear” iota profile (0.39–0.65).
  - stabilize neoclassical tearing modes.
- 3/4 of edge iota (B-poloidal) from external coils.
  - 1/4 from bootstrap current.



Coil Design Satisfies Physics and Engineering Criteria

- NCSX design uses 18 modular coils (3 shapes)
  - Also TF, PF, and helical trim coils.
- Free-boundary VMEC-based method was developed to optimize coils for low-R/⟨a⟩, current-carrying stellarators.
  - D. J. Strickler, et al., FT/P2-06 (Fri. p.m.)
- Required properties are realized:
  - Free-boundary equilibrium with the required physics properties (R/⟨a⟩, QA, stability at $\beta = 4\%$, iota profile).
  - Engineering feasibility metrics: coil-coil spacing, min. bend radius, tangential NBI access, coil-plasma spacing.
  - Good magnetic surfaces.

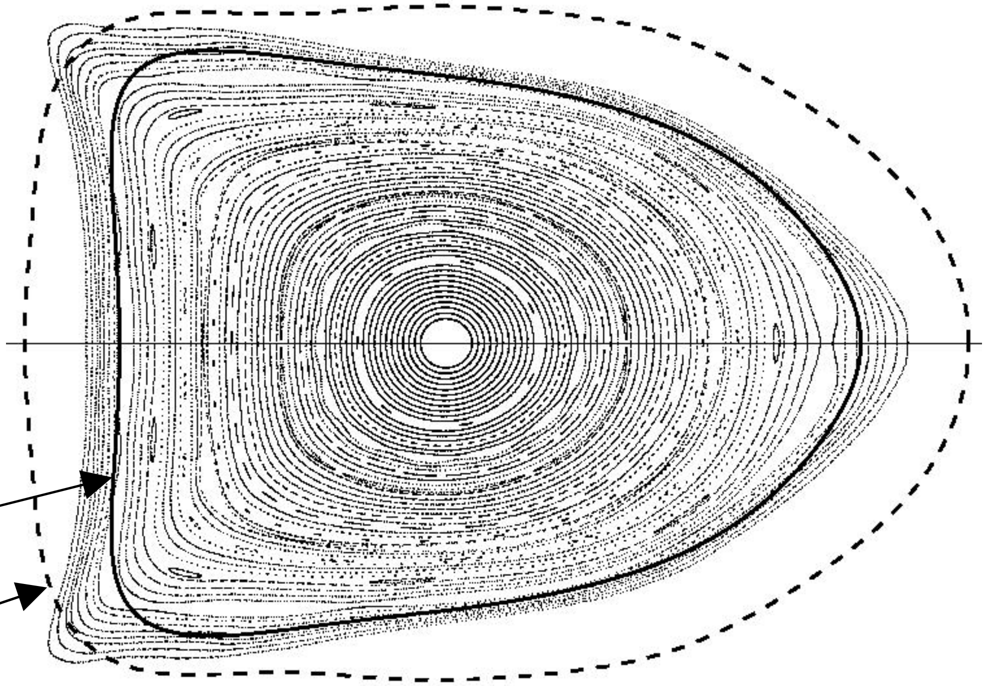


Coil Design Produces Good Surfaces at High β

- Coil geometry adjusted to “heal” islands (measured with PIES code) while preserving physics and engineering properties.
  - – S, R. Hudson et al, next talk.
- Corrections for neoclassical and finite $\chi_\perp/\chi_{||}$ effects (not included in PIES calculation) reduce effective island width by factor 2-3.

- Free-boundary PIES equilibrium for β = 4%.
- Multi-filament coils.

Sum of effective island widths is <1%.



VMEC plasma boundary with unhealed coils

First wall boundary

Also, good surfaces in a range of vacuum configurations.

A Wide Range of Plasma Conditions Is Accessible

Machine Parameters

- $R = 1.4$ m
- $B = 1.2 - 2.0$T
- $P_{NBI} \leq 6$ MW (tangential access, 0.3 s pulse)
- $P_{RF} \leq 6$ MW (high-field-side launch)

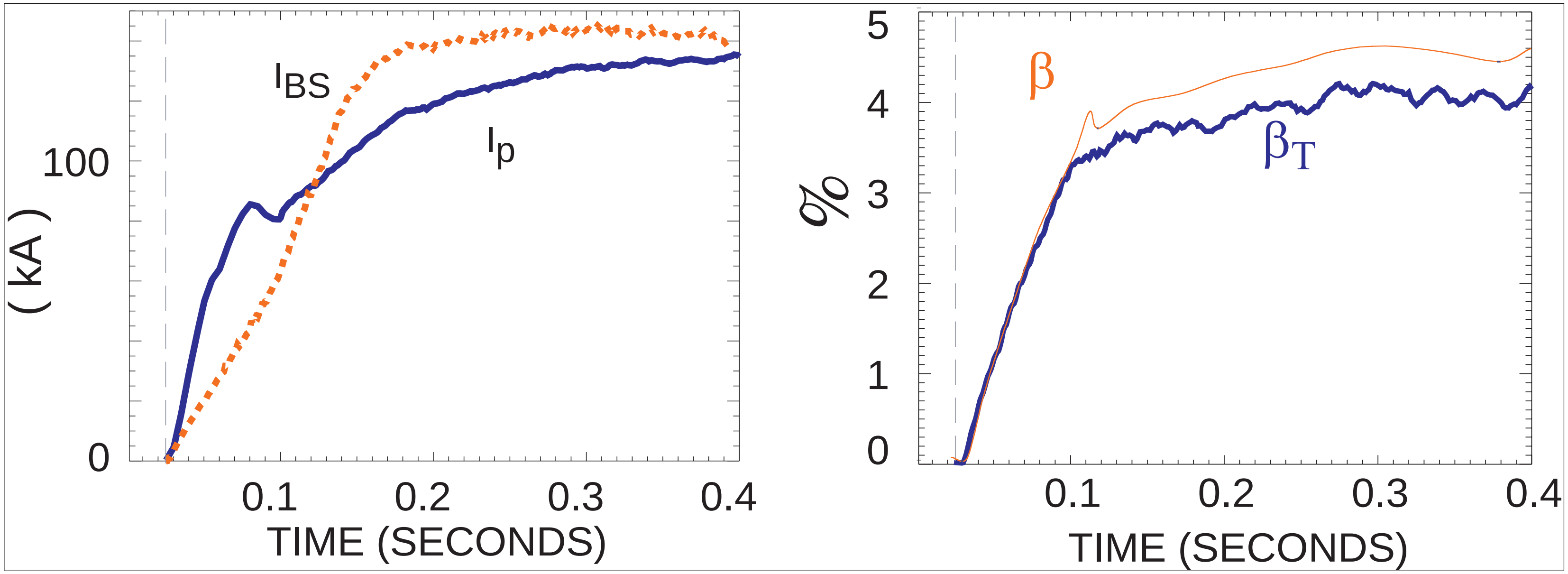
$\beta = 4\%$ at $B = 1.2$ T, $P = 6$ MW (assuming $\tau_E = 2.9 \times$ ISS95 $\approx$ L-mode)

- $n_e = 6 \times 10^{19}\ m^{-3}$
- $T_i(0) = 1.8$ keV
- $\nu_i^* = 0.25$

Many regimes available to test physics

- Low ν_i^* (~0.1), high T_i ($\leq$2.5 keV) with $B \rightarrow 2$ T.
- High n_e ($\leq 1.6 \times 10^{20}\ m^{-3}$) Sudo limit at $B = 1.2$ T.
- Long pulse ($\leq$ 1.7 s) with heating upgrades.

Profile Evolution: Vacuum to High-Beta



New method uses TRANSP code to simulate time evolution of profiles in equivalent tokamak configuration.

- External iota simulated as externally driven current.
- Ohmic startup: $V_{loop} \approx 1$ V, clamped after initial 1.5 MA/s current rise.
- 6 MW NBI: balanced to control iota perturbation from NBCD, modulated to control pressure.
- Assumed empirical τ_E = min(neo-Alcator, L-mode)

Reaches all-bootstrap target state with $\beta \approx 4\%$ after 0.3 s of heating.

Coils Provides Stable Access Path to High Beta

Transformation to stellarator equilibrium uses free-boundary VMEC with simulated profiles, NCSX coils.

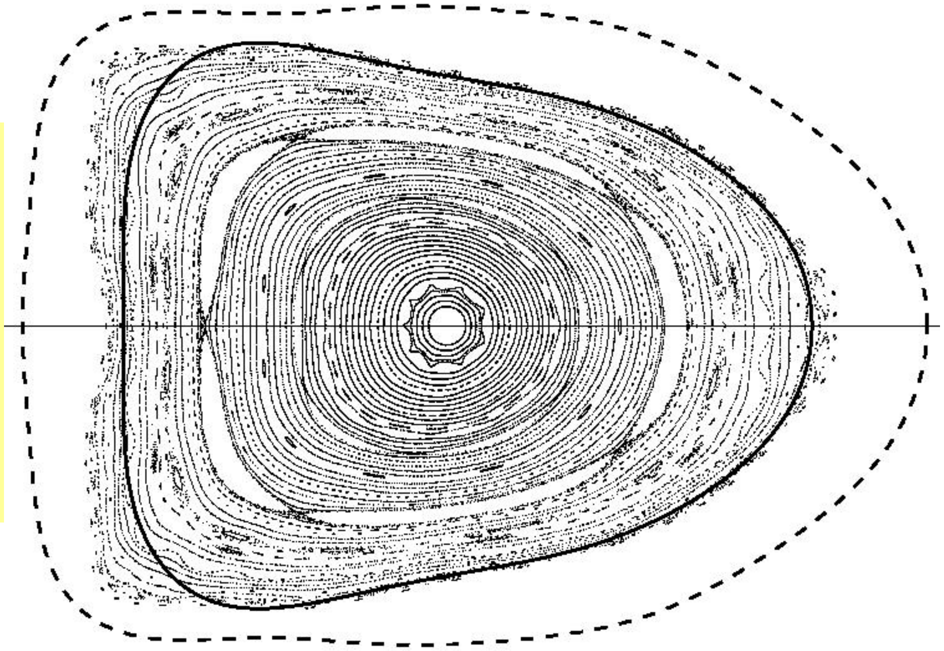
Good properties calculated along the discharge trajectory.

- Quasi-axisymmetric ($\epsilon_{h,eff}$ < 0.4% at r/a = 0.5)
- Stable to ballooning and kink modes.
- Good magnetic surfaces.

Magnetic surfaces at t = 0.3 s
(β = 4.5%)

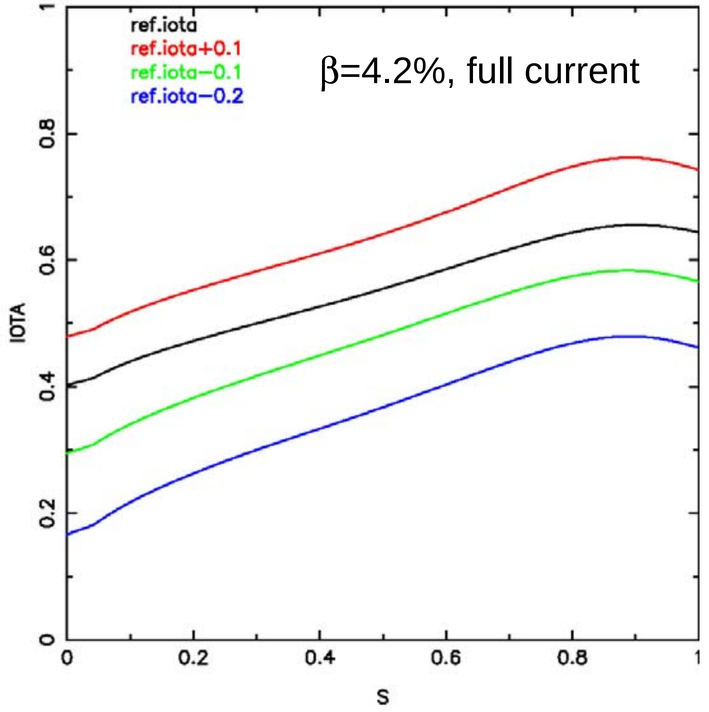
- Effective m=5 island area ≈ 2.5% with neoclassical correction. (5% in PIES calculation)

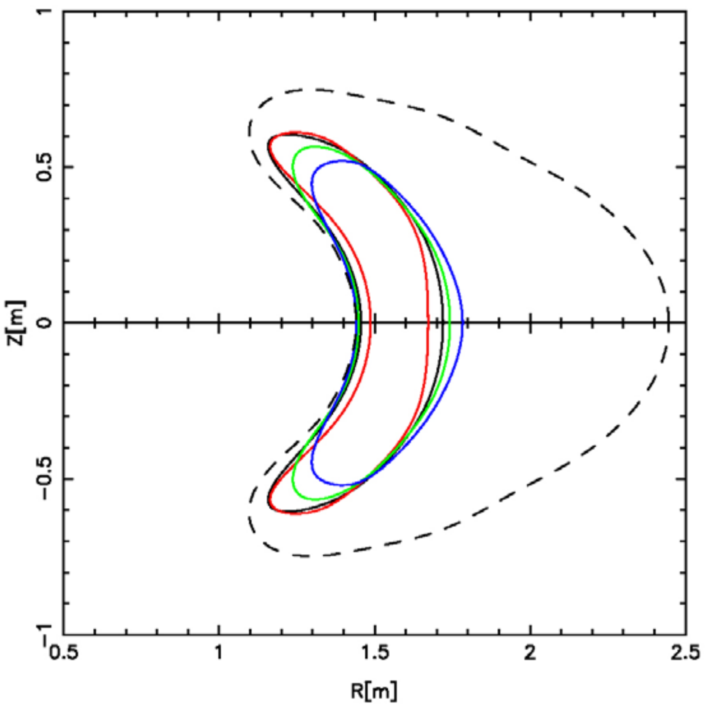
- Island width can also be reduced with trim coils.



Free-boundary PIES calculation

NCSX Coils: Flexibility to Vary Physics Properties





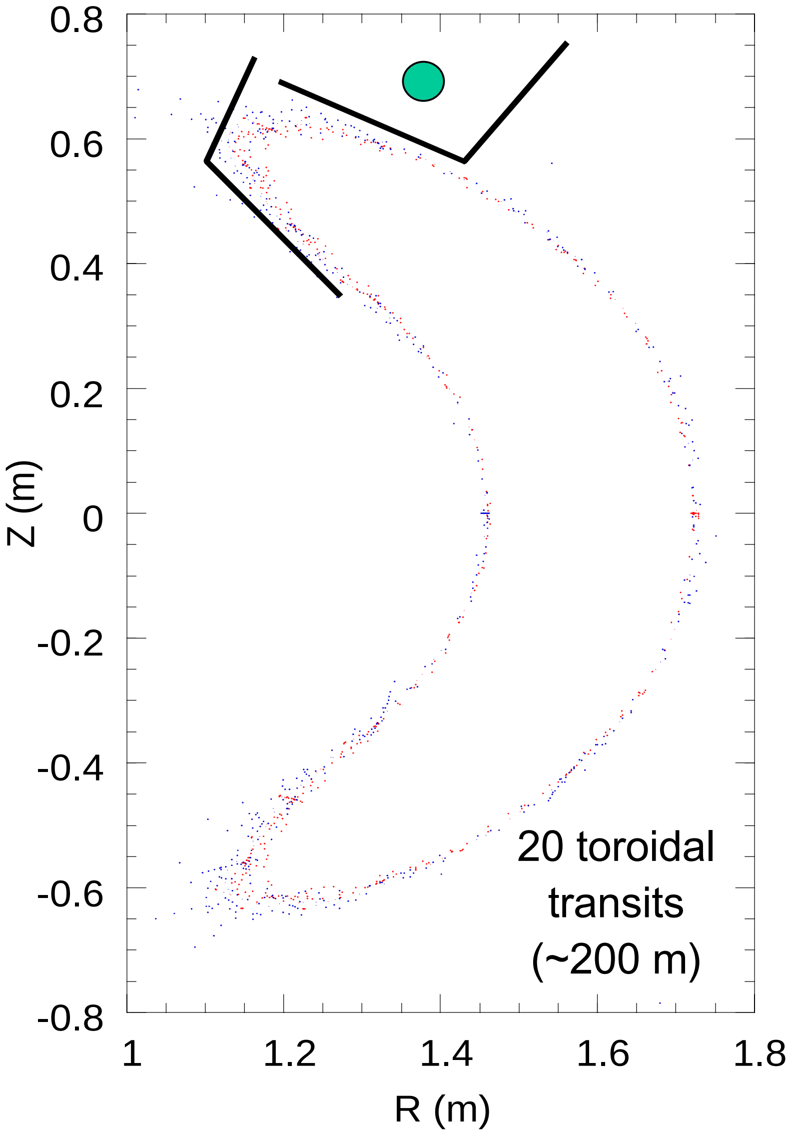
External iota controlled by plasma shape at fixed profiles.

Also

- Can externally control shear.
- Can increase ripple by ~10x, preserving stability.
- Can lower theoretical β-limit to 1%.
- Can cover wide operating space in β (to at least 6%), I_P, profile shapes.

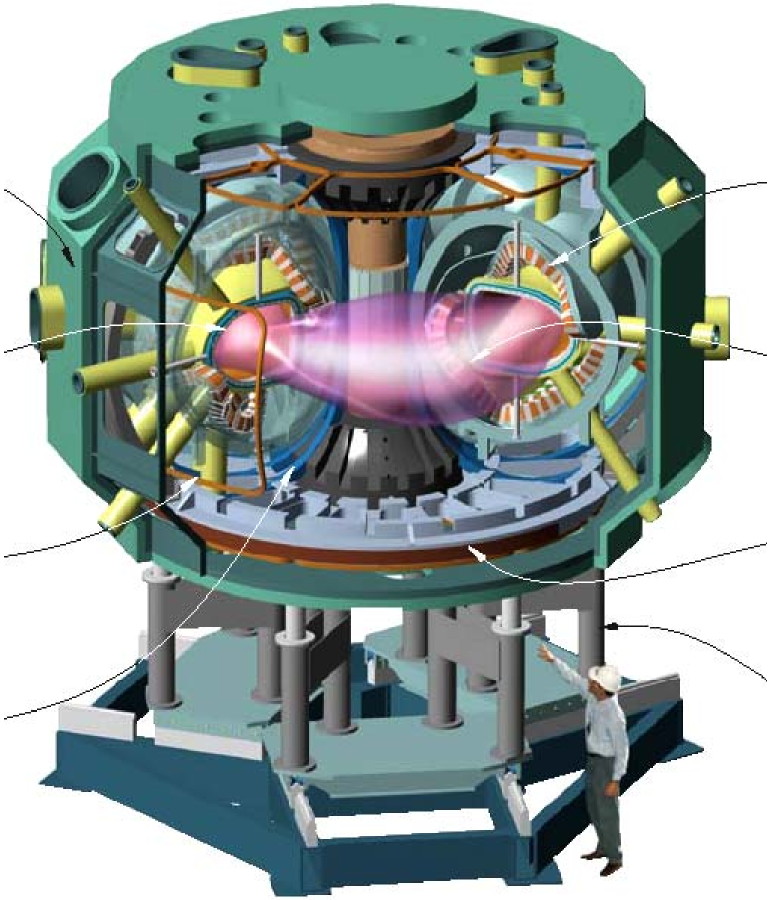
Edge Field Lines Have Long Connection Lengths

- L > 100 m desired for low-temperatures at target → impurity control
- Ordered (not stochastic) field line structure, expands near tips of bean cross-section (envisioned divertor location).
- Field lines stay close to boundary except near divertor.
  - Sets criteria for first wall placement to ensure long connection lengths.



NCSX Physics Design Summary

- Optimized for high-beta compact QA plasma with attractive physics properties.
- Access to high-beta state starting from vacuum.
- Flexibility for physics experiments.
  - Knobs to vary physics properties.
  - Large operating space in β, I_P, profile shapes.
  - Range of operating scenarios (high β, low ν^*, long pulse).
- Space for divertor and first wall.
- Ample port access.
- Feasible engineering design.
  - Engineering: B. E. Nelson, et al., FT/2-4.



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